Argonne NATIONAL LABORATORY

... for a brighter future

Why Do We Need a PS X-Rays Source?

Deflecting Cavities for Light Sources

Ali Nassiri

Advanced Photon Source

LHC-CC08 Mini-Workshop

Brookhaven National Laboratory

February 25-26, 2008

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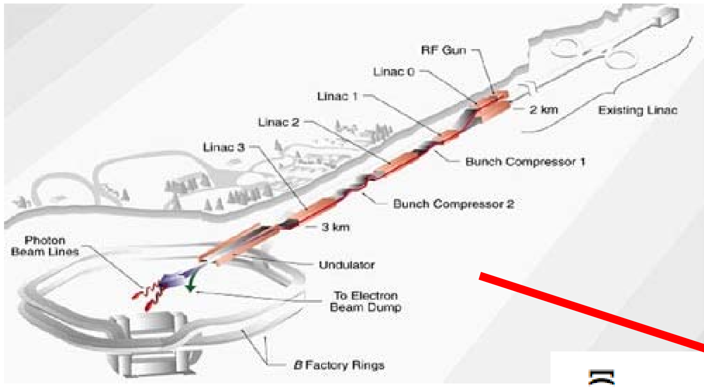
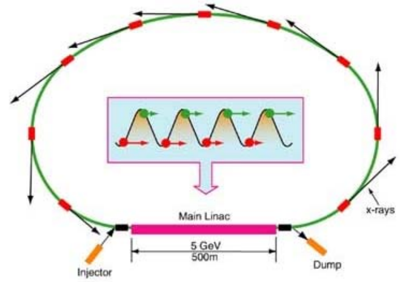
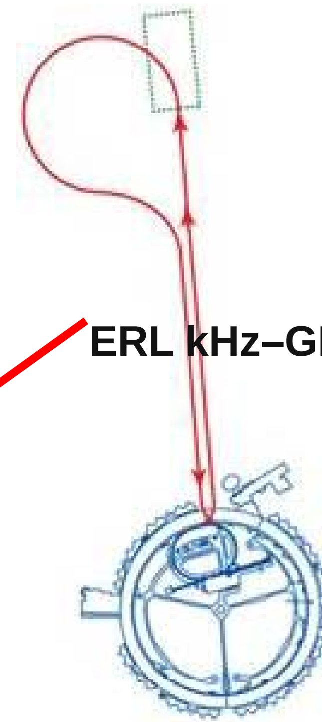
Outline

- Science case
- Rf crabbing concept
- X-ray performance
- Beam dynamics issues
- Technology options and challenges
- Summary

A New Era of Ultrafast X-ray Sources

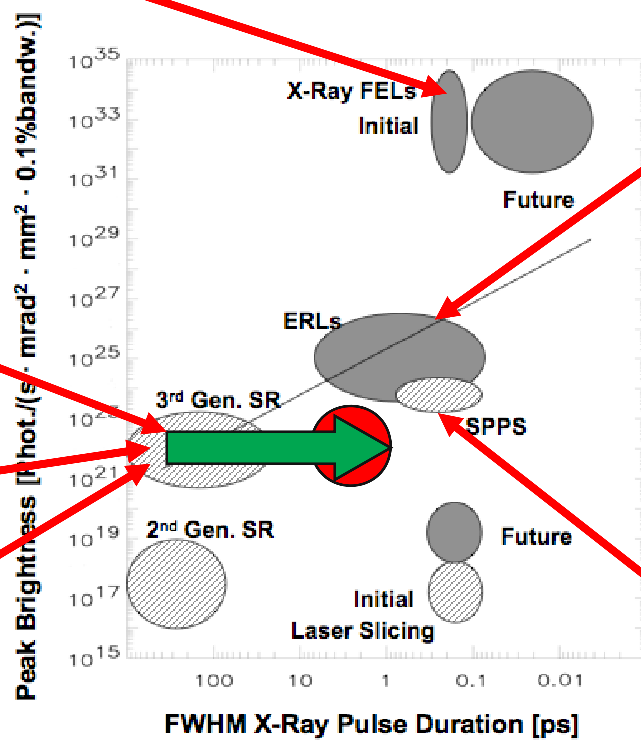






ERL kHz–GHz

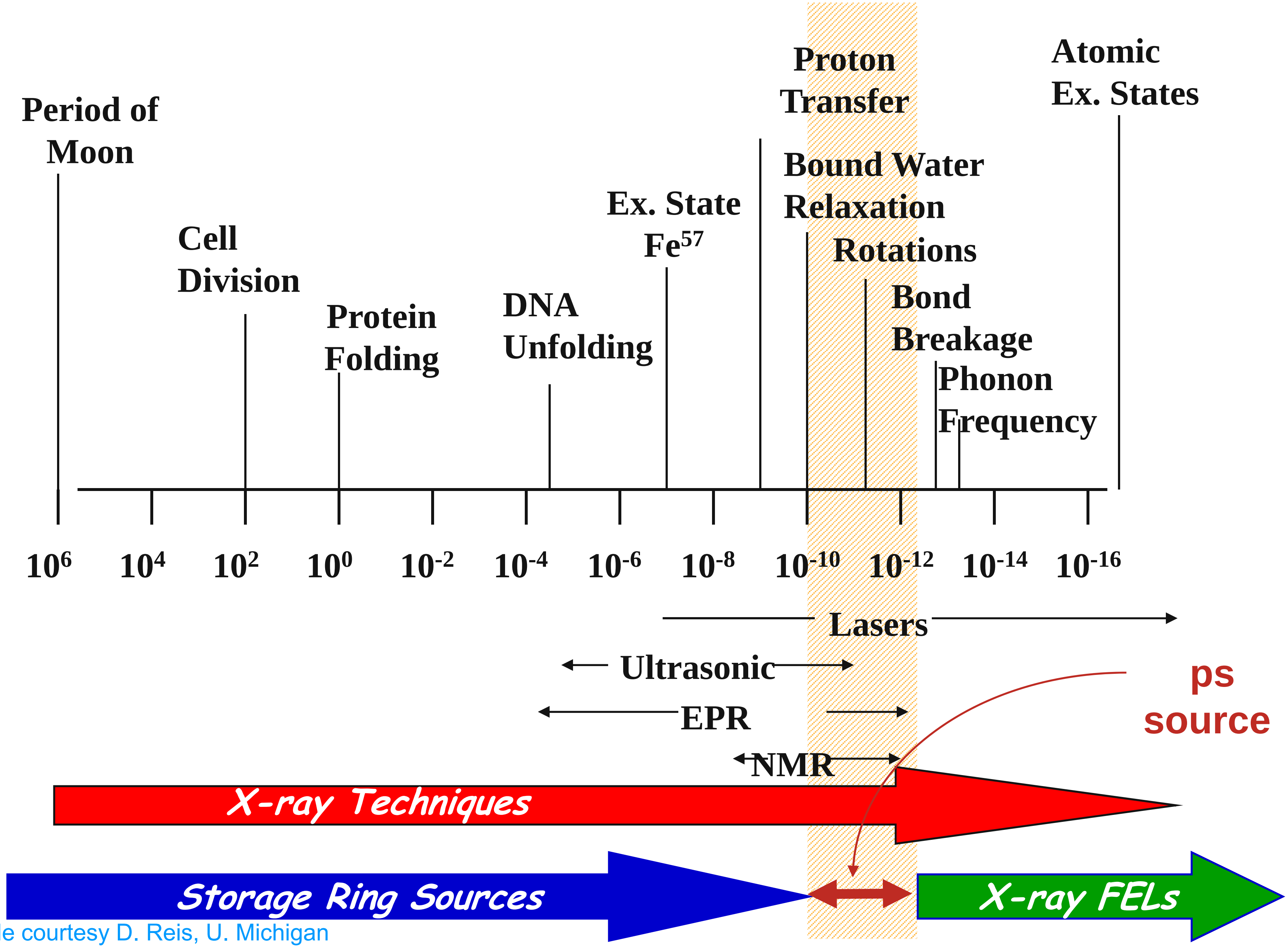
LCLS: 120Hz



SPPS 10Hz

ps upgrade 120–1kHz,?)

Slide courtesy: D. Reis, UM



Slide courtesy D. Reis, U. Michigan

Science Enabled by ps Sources

- The field of time domain scientific experiments using hard x-rays from synchrotron radiation sources is gaining momentum.

- The time range covered by ongoing and future experiments is from sub-picoseconds to thousands of seconds which is 16 to 17 decades of spread.

- The scientific disciplines which will benefit from these studies include:
  - Atomic and molecular physics
  - Biology and chemical science
    - *Photochemistry in solution*
  - Condensed matter physics
    - *Ultrafast solid state phase transition*
  - Engineering and environmental science
  - Material and nuclear science

Existing and Future Sources

- Table-top plasma sources
  - **Short pulse 300 fs - 10 ps**
  - **Divergent radiation - low flux**
  - **Low rep-rate (10- 1kHz)**
  - **Not tunable (target dependent)**
- Storage Rings
  - **~100-ps duration pulse**
  - **Spontaneous x-ray radiation**
  - **High average brightness at high repetition rate**
- Laser Slicing (ALS, SLS, BESSY)
  - **Short pulse 100 -300 fs**
  - **Rep-rate kHz**
  - **Low flux 105 ph/s @ 0.1%bw**
  - **Not effective at high-energy sources**
- Linacs (LCLS/XFEL)
  - **Short pulse 100 fs**
  - **Fully coherent**
  - **Extremely high brilliance**
  - **Low rep-rate (100 Hz)**
  - **Limited tunability**

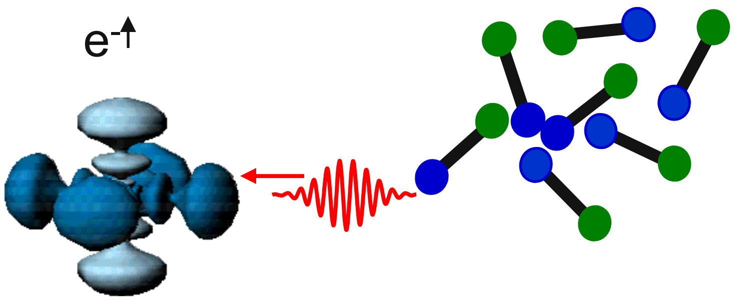
What do the Users Want?

- Peak brightness isn't everything
- What is important is a combination of:
  - Short pulse (1ps or below)
  - Tunability
  - Repetition rate (1 kHz to CW)
  - Accessibility
  - Average number of photons
  - Focusibility

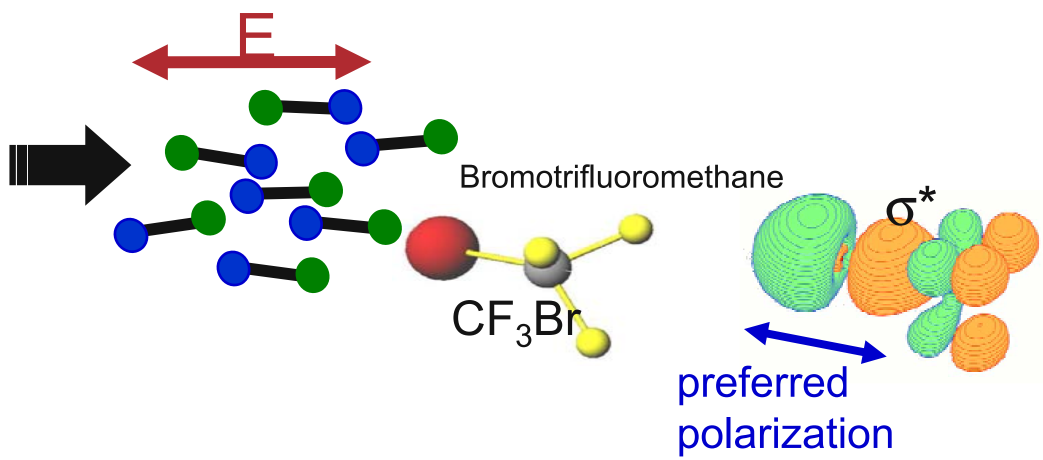
Flexible source will enable new physics

- Coherent diffraction imaging of molecules at higher field strength
  - Monitor laser-induced distortion with sub-Angstrom resolution
  - Current 10^{12} W/cm^2 @ 100 ps to 10^{14} W/cm^2 @1ps
  - Test ab initio understanding of dynamics polarizability
  - Non-perturbative multiphoton effects
- Coherent diffraction imaging of molecules in a field-free environment
- Dynamics of laser-controlled motions: rotational and vibrational (phonon)
- Photoionization dynamics from aligned molecules

Dipole interaction between molecules and laser electric field
short x-ray pulse (ps) is essential to match the alignment time scale



Orbital alignment in ultrafast field ionization
10^{14}-10^{15} W/cm^2

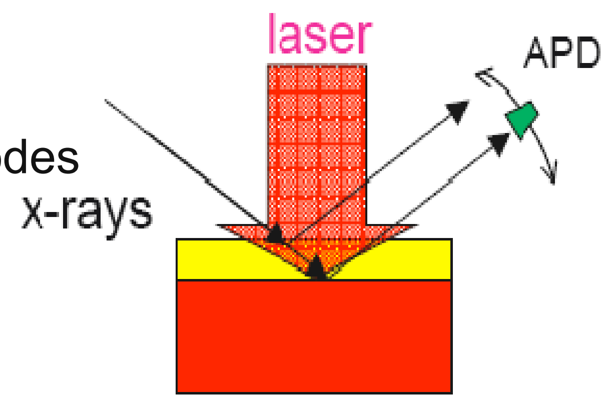


Slide courtesy: L. Young, AMO Group, ANL

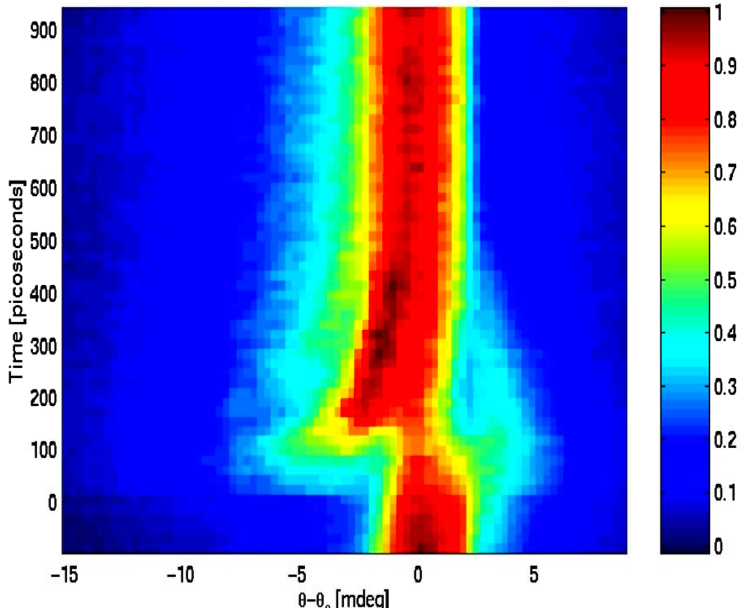
X-ray absorption by laser-aligned molecules ~10^{12} W/cm^2

Time-resolved Bragg Diffraction: (laser pump/x-ray probe)

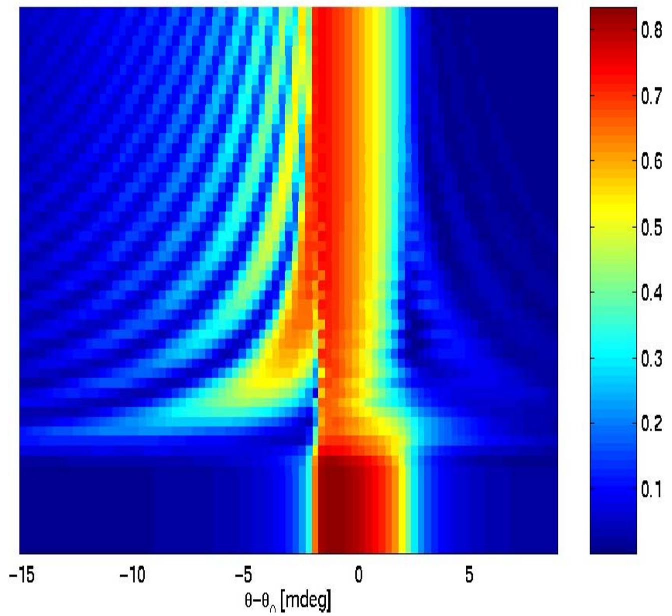
- Coherent Acoustic Phonons
- Impulsive strain propagation in Indium Antimony
- Quantitative measurements of atomic displacements
- Track energy flow from optical excitation into lattice modes



Time-resolved x-ray diffraction
proportional mode



Experiment: InSb 111, 10mJ/cm^2

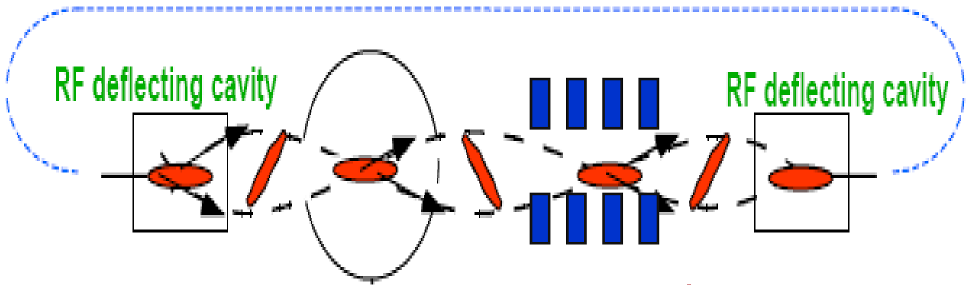


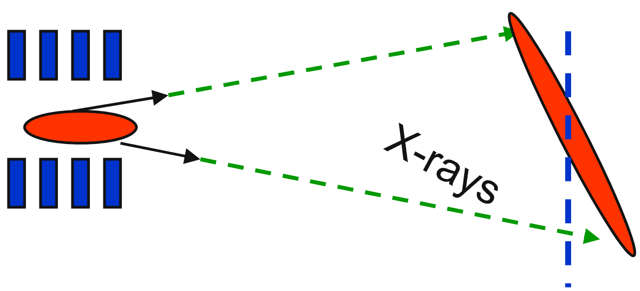
Simulation: 100ps & 1.25mdeg conv.

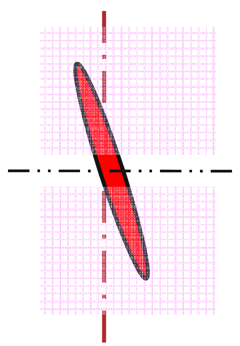
Reis *et al.* Phys Rev. Lett.(86) 2001

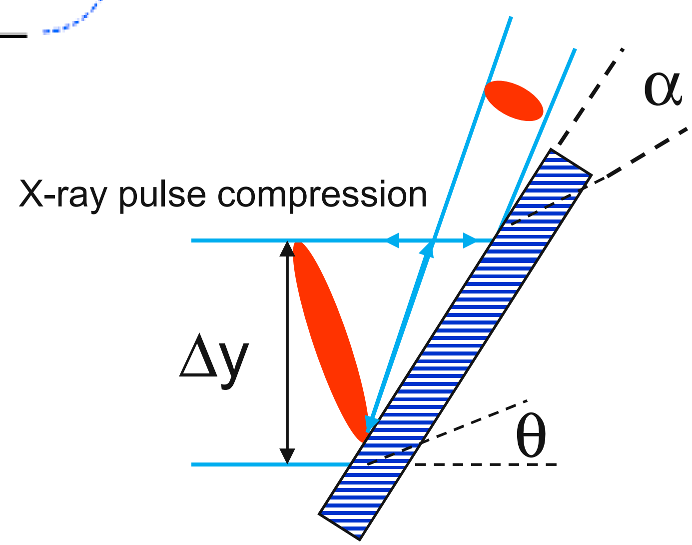
Concept

- Use transverse-deflecting rf cavities to impose a correlation (“chirp” between the longitudinal position of a particle within the bunch and the vertical momentum.
- The second cavity is placed at a vertical betatron phase advance of *n*π downstream of the first cavity, so as to cancel the chirp.
- With an undulator or bending magnet placed between the cavities, the emitted photons will have a strong correlation among time and vertical slope.
- This can be used for either pulse slicing or pulse compression.



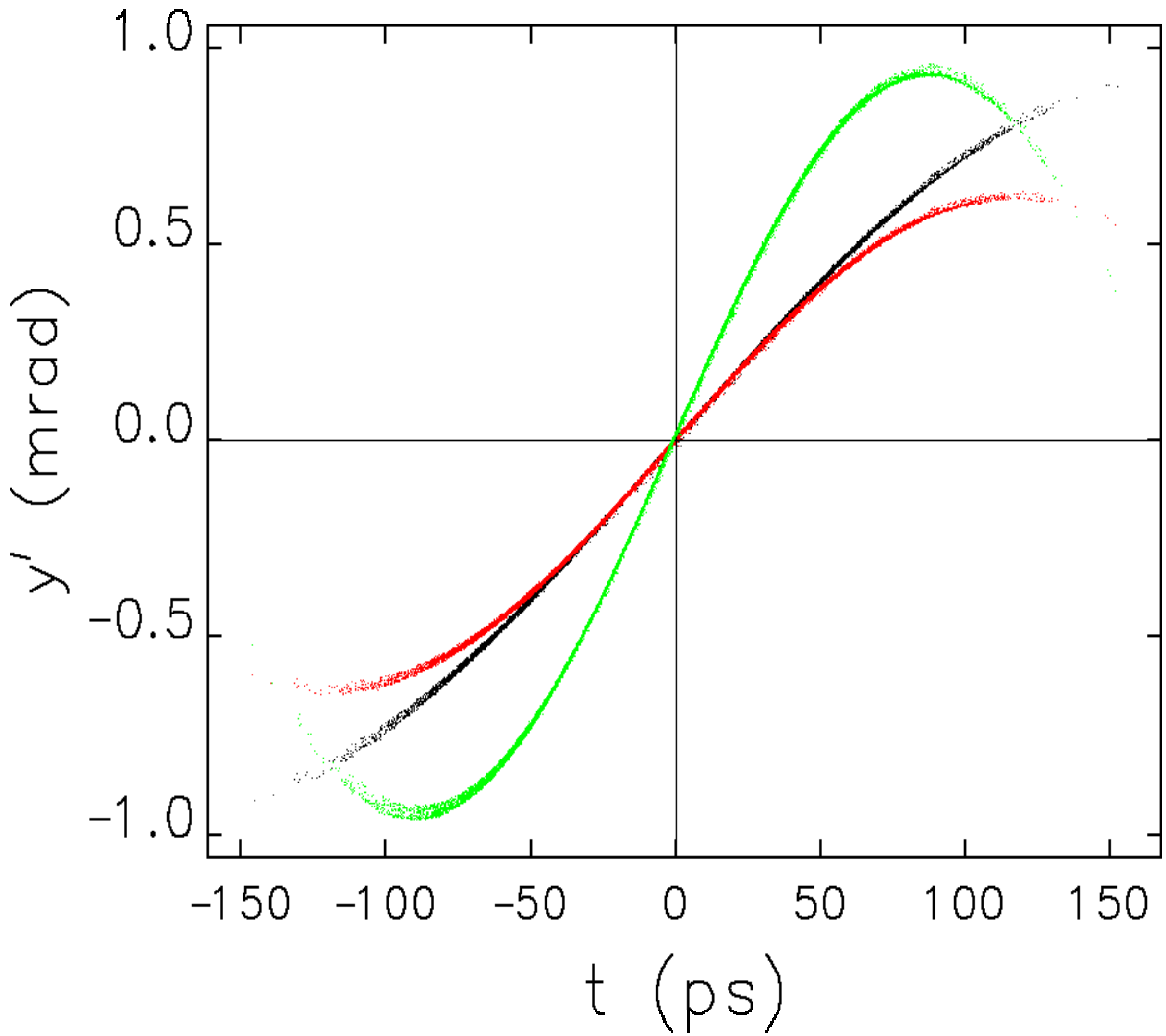






A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A 425(1999), 385

Rf Curvature and Frequency Choice



Can get the same compression as long as h*V is constant.

Higher h and lower V: smaller maximum deflection and less lifetime impact.

Higher V and lower h: more linear chirp and less need for slits.

Higher h and maximum V: shortest pulse, acceptable lifetime

X-ray performance

Electron beam energy

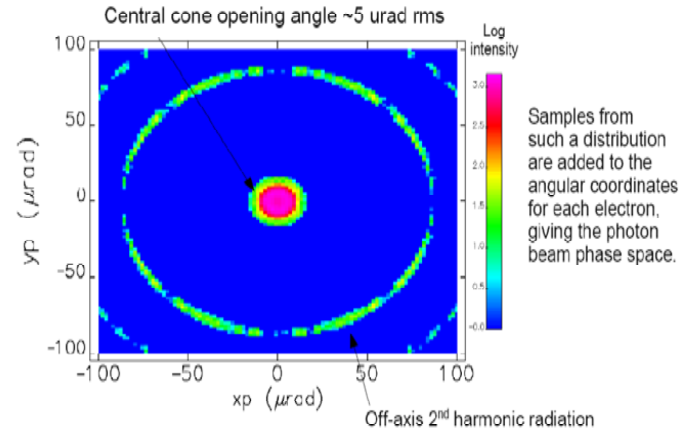
$$\sigma_{t,xray} \approx \frac{E}{V h \omega_a} \sqrt{\frac{\beta_{id}}{\beta_{rf}}} \sqrt{\sigma^2_{y',e} + \sigma^2_{y',rad}}$$

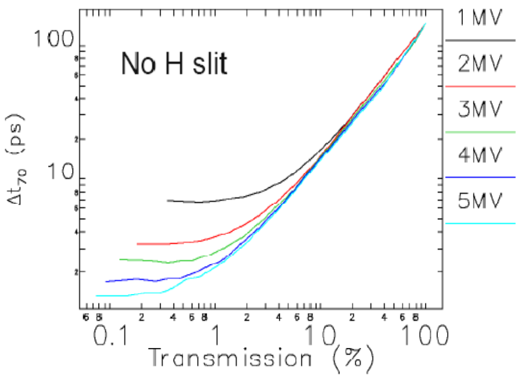
→ For 4 MV, 2800MHz (h=8) deflecting system, get ~0.6 ps

Deflecting rf voltage & frequency

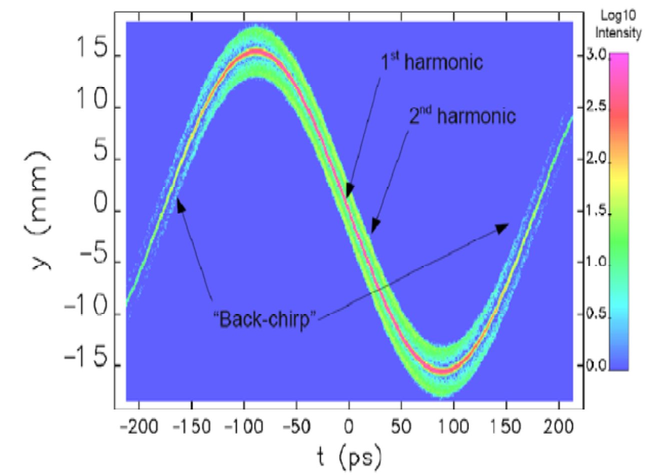
Unchirped e-beam divergence (typ. 2-3 μrad)

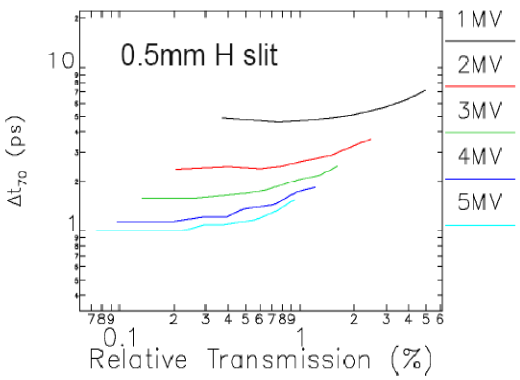
Divergence due to undulator (typ. ~5 μrad)





- Without horizontal slits, intensity reduction of about 100x to reach 2 ps FWHM
- However, beamline is normally operated with 0.5 mm and 0.5 mm H and V slits
  - The intensity reduction relative to this case is about the same





26.5 m is the distance to a 2mm × 3mm aperture in the ID7 beamline. Aperture is typically set 0.5 mm in both planes. (E. Dufrense)

Data courtesy R. Dejus

Plots courtesy M. Borland

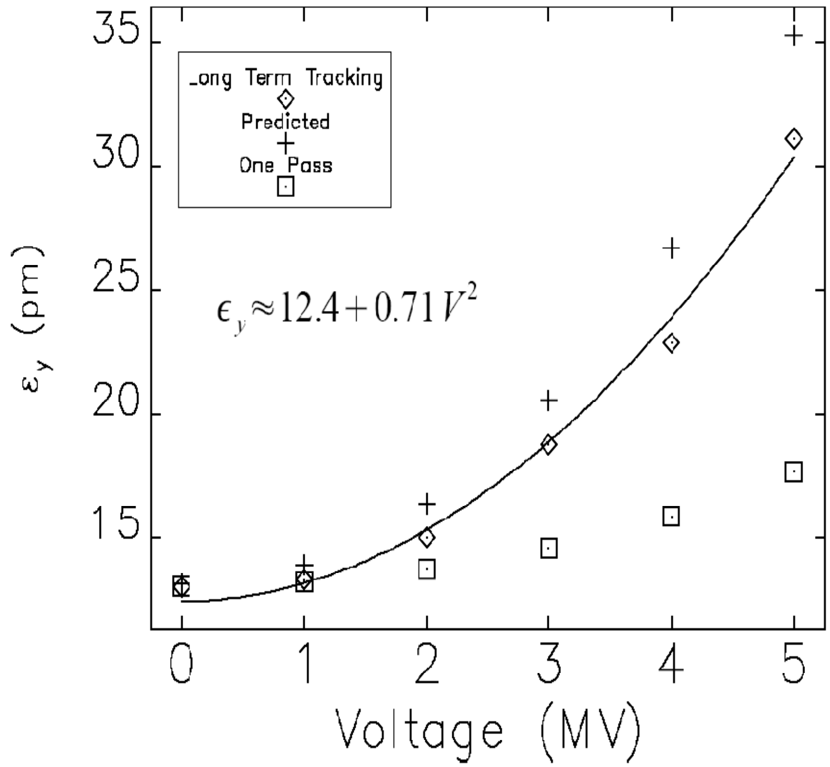
Beam dynamics issues – emittance growth[1]

- In an ideal machine
  - TOF dispersion between cavities due to beam energy spread
  - Uncorrected chromaticity
  - Coupling of vertical motion into horizontal plane by sextupoles
  - Quantum randomization of particle energy over many turns
- Additional source of growth – real machine
  - Errors in magnet strengths between the cavities
  - Roll of magnets about beam axis
  - Orbit error in sextupoles
  - Errors in rf phase and voltage
- Side effects
  - It limits brightness
  - It limits how short an x-ray pulse can be acheived

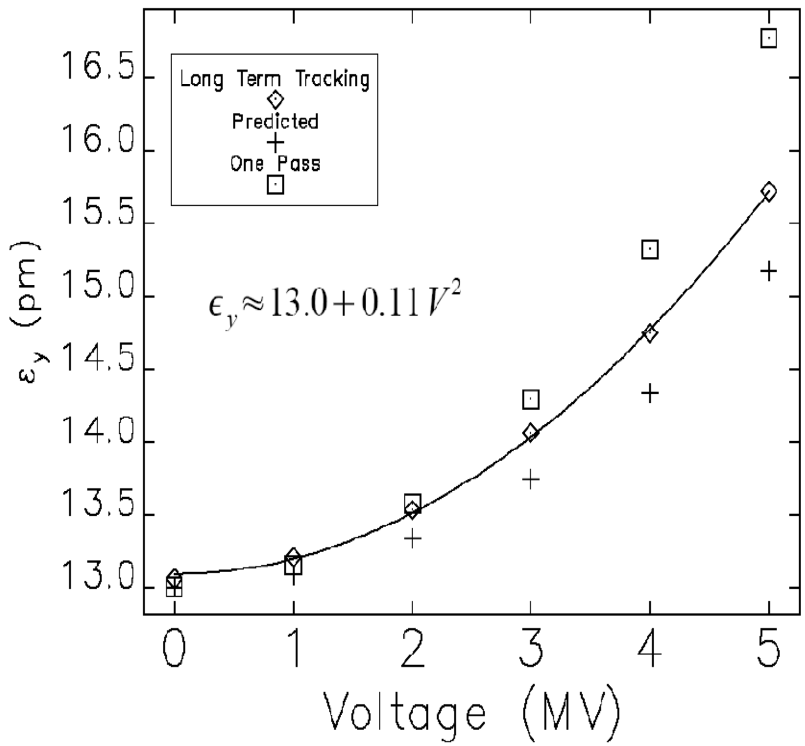
[1] M. Borland, Phys. Rev. ST Accel Beams 8, (2005)

Emittance growth vs. deflecting voltage

Target Bunch Emittance Growth for 1 kHz Pulse Rate



Results for 120 Hz Pulse Rate



Plots courtesy M. Borland

Summary of Tolerances

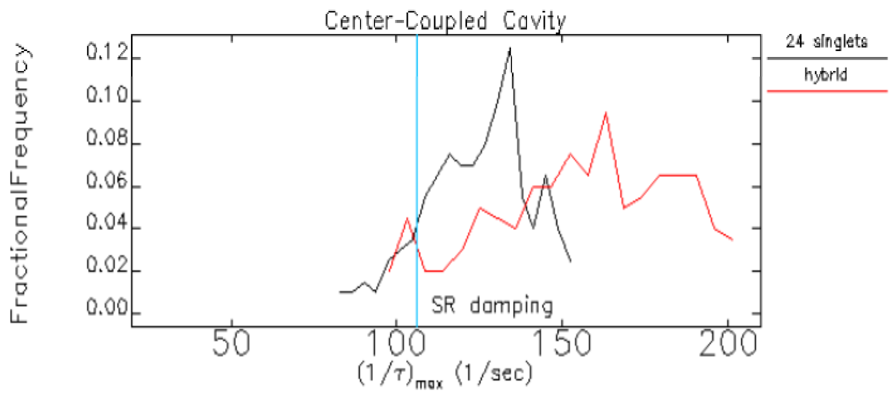
Quantity	Driving Requirement	120 Hz Tolerance	1 kHz Tolerance
Common-mode voltage	Keep intensity and bunch length variation under 1%	±1%	±1%
Differential voltage	Keep emittance variation under 10% of nominal 25 pm	±0.29%	±0.13%
Common-mode phase relative to bunch arrival	Constraint intensity variation to 1%	±10 deg	±10 deg
Differential phase	Keep emittance variation under 10% of nominal 25 pm	±0.16 deg	±0.05 deg
Rotational alignment	Emittance control	~1 mrad	~1 mrad
Net residual voltage	Emittance control (weak bunches)	26 kV	13 kV

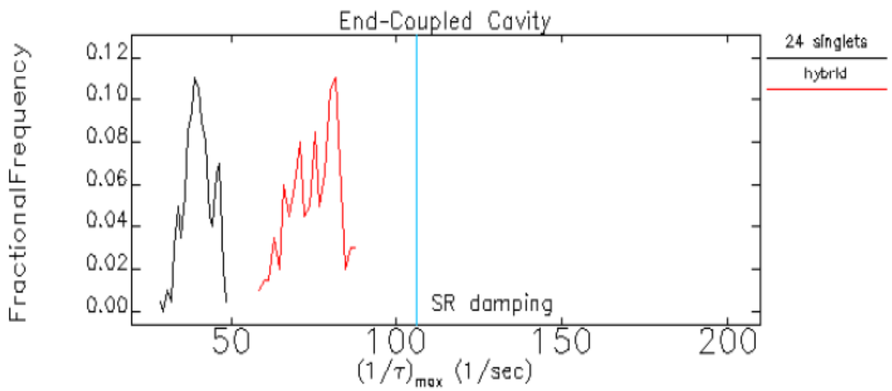
- Differential errors are assumed to be "static"
- CM errors may be dynamic, but conservatively evaluated as static
- Temperature control should be AGARA. We'll have to manage temperature-related drifts with phase shifters and attenuators.
- Tolerance on timing signal from crab cavity to users: ±0.9 deg

Slides courtesy M. Borland

Beam stability Analysis - HOM/LOM

- For three-cell cavities with coupler at end cell using 3D model for R, Q, and R/Q values
- Qs of longitudinal and horizontal planes are very low (20 – 200)
- Worst vertical plane HOM has a Q of 4100
- Horizontal and vertical planes are stable with synchrotron radiation
  - No need for coherent damping

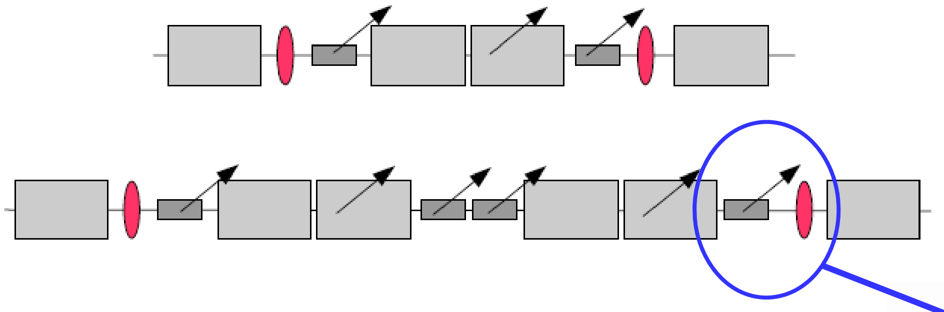




Plane	Growth Rate	Damping Rate		Comment
		Synchrotron Radiation	Coherent	
Longitudinal	60 s^{-1}	208 s^{-1}	Not applicable	Stable
Horizontal	5 s^{-1}	104 s^{-1}	>600 s^{-1}	See above
Vertical	80 s^{-1}	104 s^{-1}	>600 s^{-1}	See above

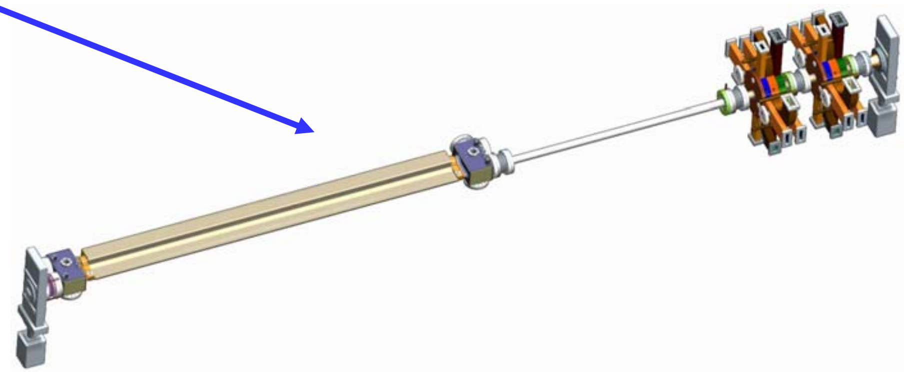
L. Emery

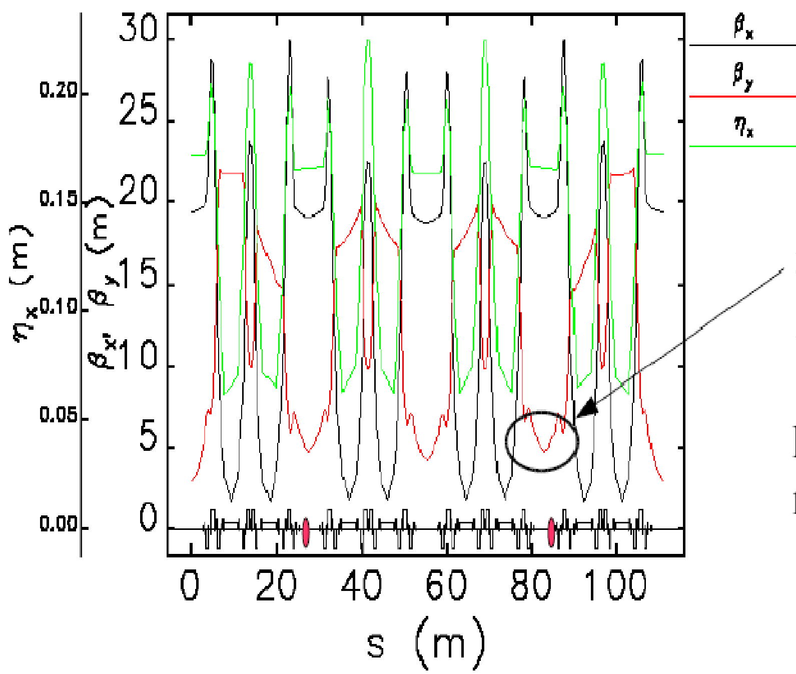
Lattice Options and Layout



1 sector spacing
2 ID + 1 BM

2 sector spacing
4 ID + 2 BM





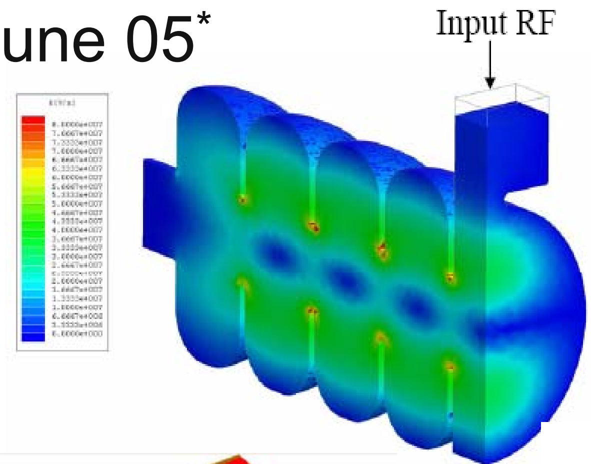
Beta function increase required to get the right phase advance

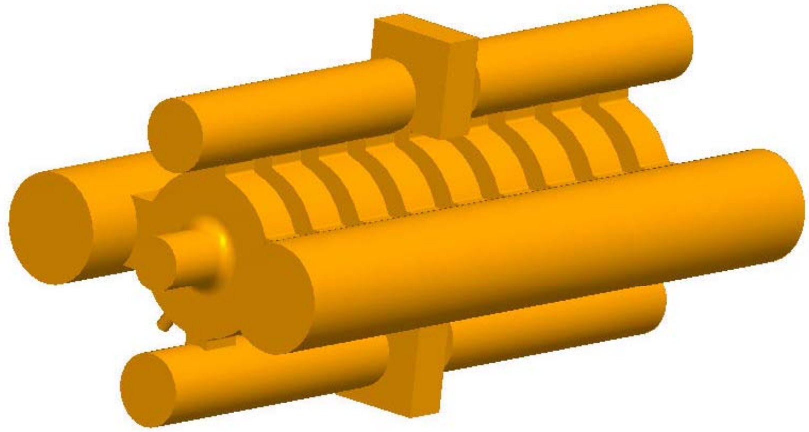
Helps compression by making divergence smaller

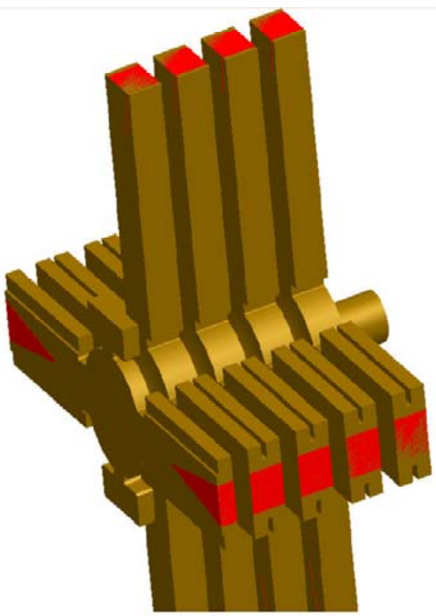
After V. Sajaev

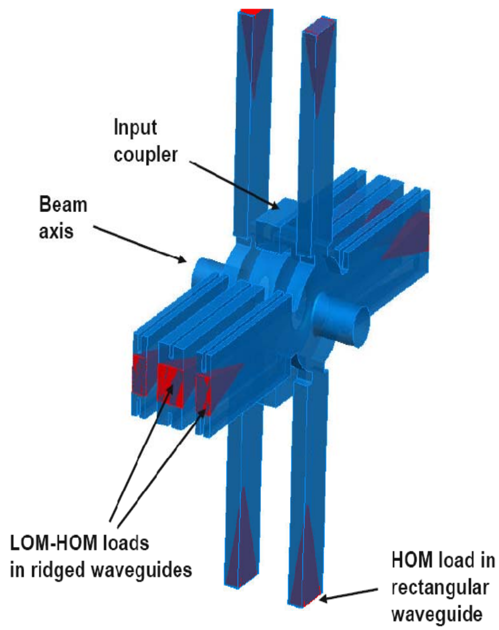
Cavity Design Evolution

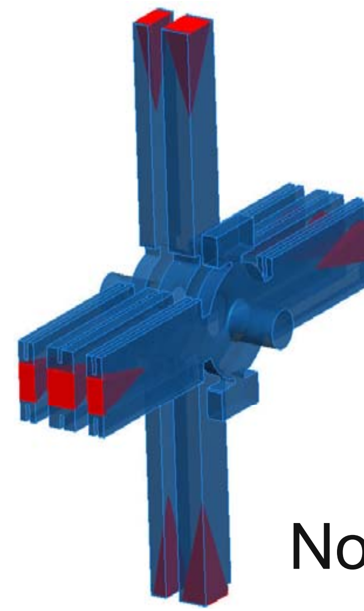
June 05*











Nov 07**

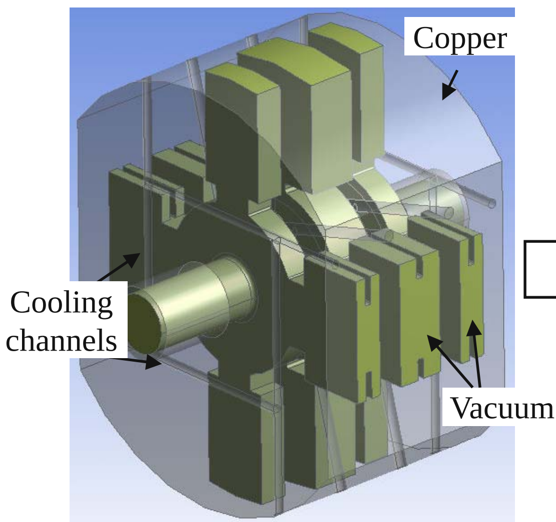
* V. Dolgashev, SLAC

** V. Dolgashev, SLAC, G. Waldschmidt, A. Nassiri

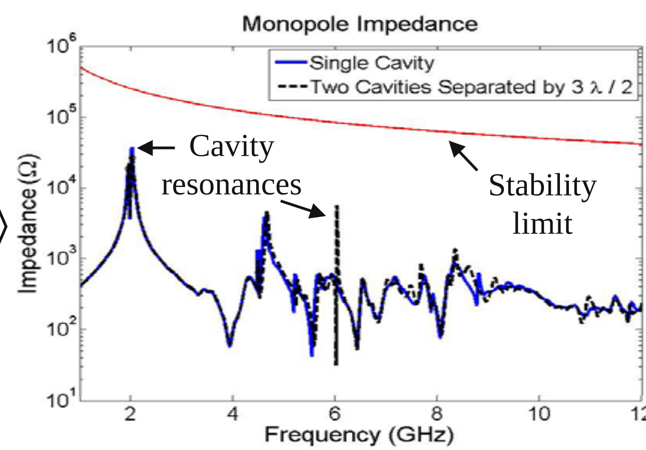
Cavity Design Flow

- Iterative process evaluated rf / physics / mechanical design and structural analysis
- Parallel analysis optimized the cavity performance
- Final analysis performed on the overall effect of structural analysis due to thermal effects on cavity rf parameters (frequency shift and modified thermal loading).

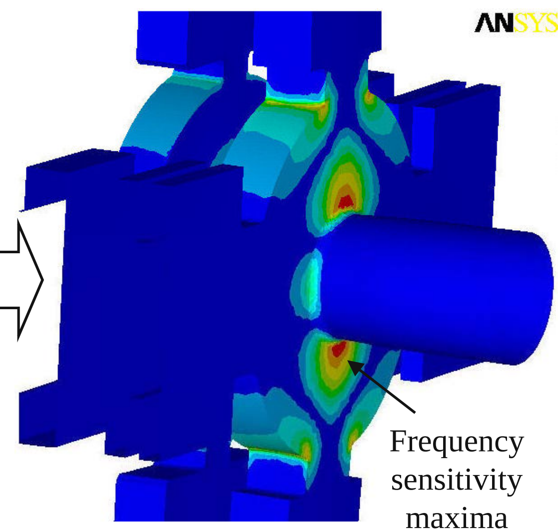
Mechanical Design



Physics Parameters



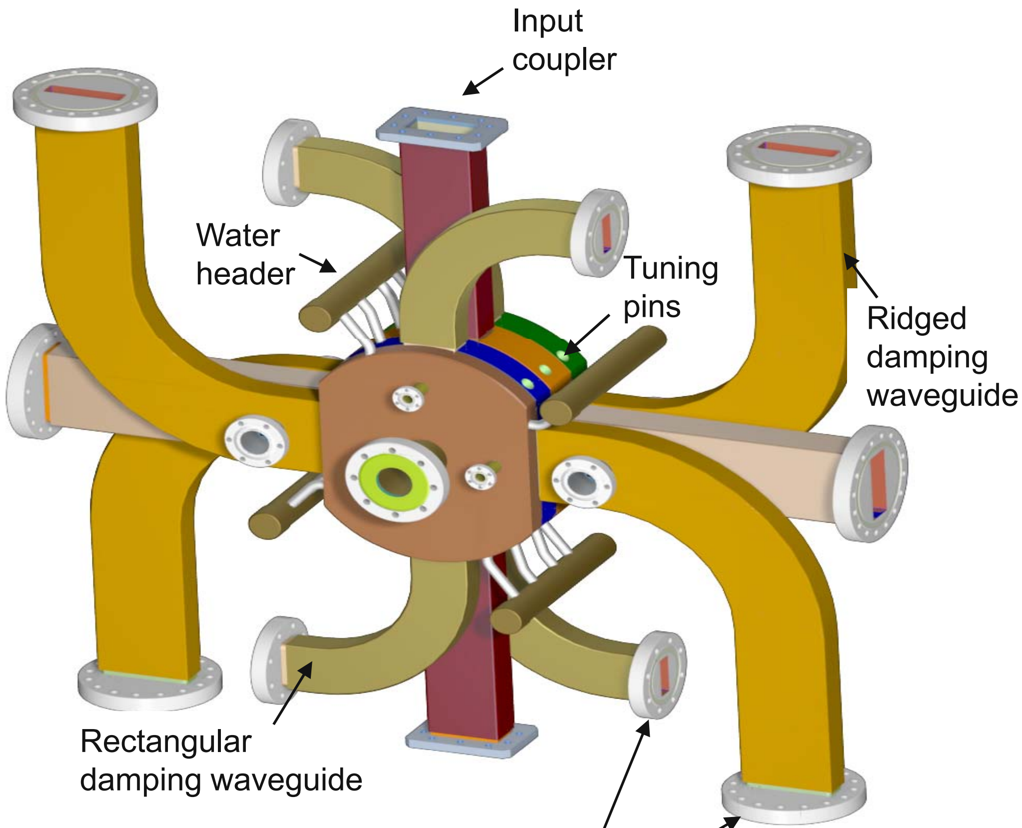
RF Parameters after Structural Analysis



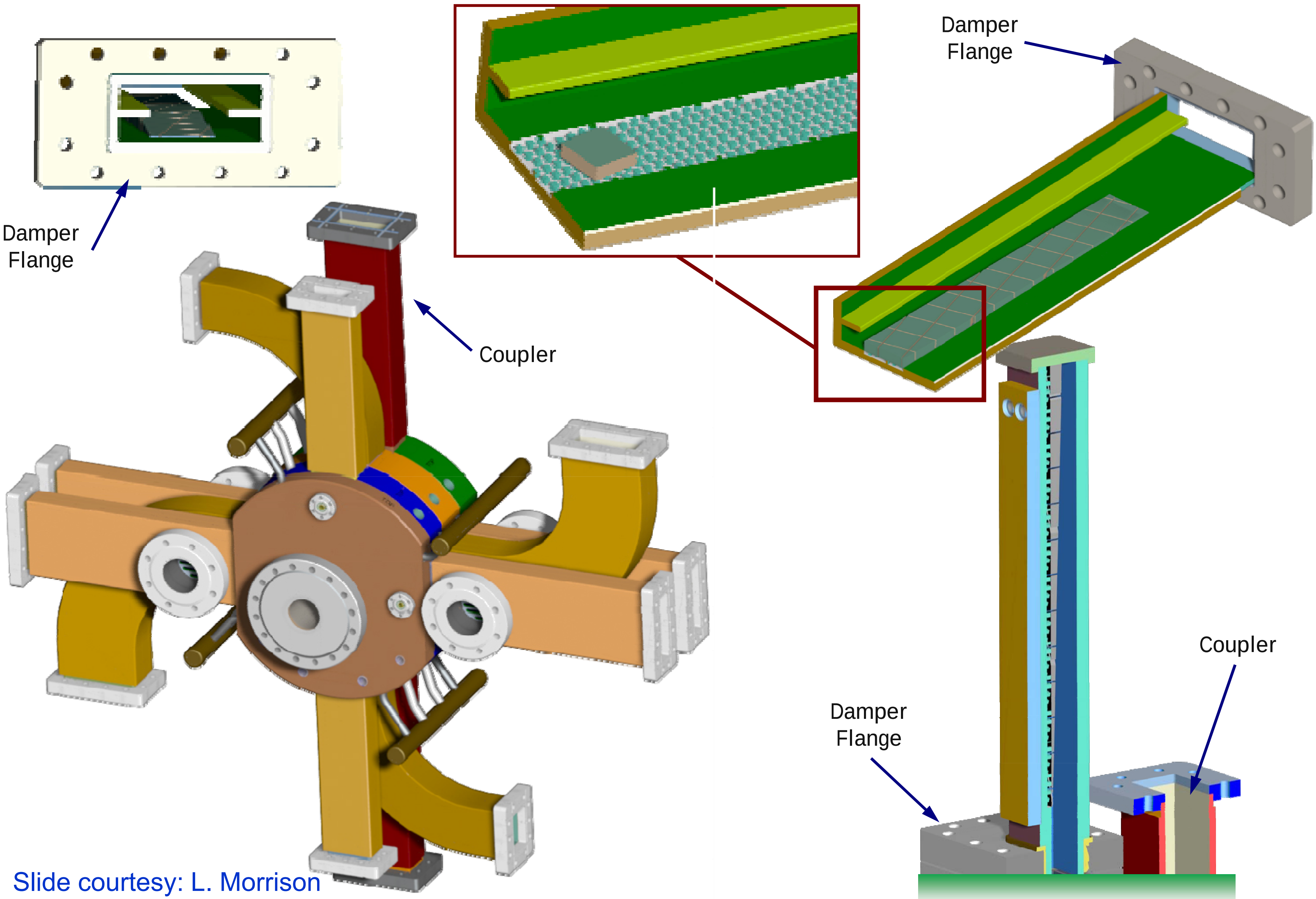
APS Short Pulse X-Ray Normal-Conducting Cavity Design*

Frequency	2.815 GHz
Deflecting Voltage	2 MV
Peak Power	2.8 MW
Working mode Q_o	12000
R_t / Q	117
Iris radius	22 mm
Phase advance	π
Structure length w/o beam pipes	11.17 cm
Duty Factor	0.147%
Pulse Rate	1.0 kHz
Kick / $(Power)^{1/2}$	1.19 $MV/MW^{1/2}$
Beam Current	100 mA

Normal-conducting 3-cell cavity with damping waveguide and dual input couplers



*Collaboration with V. Dolgashev (SLAC)

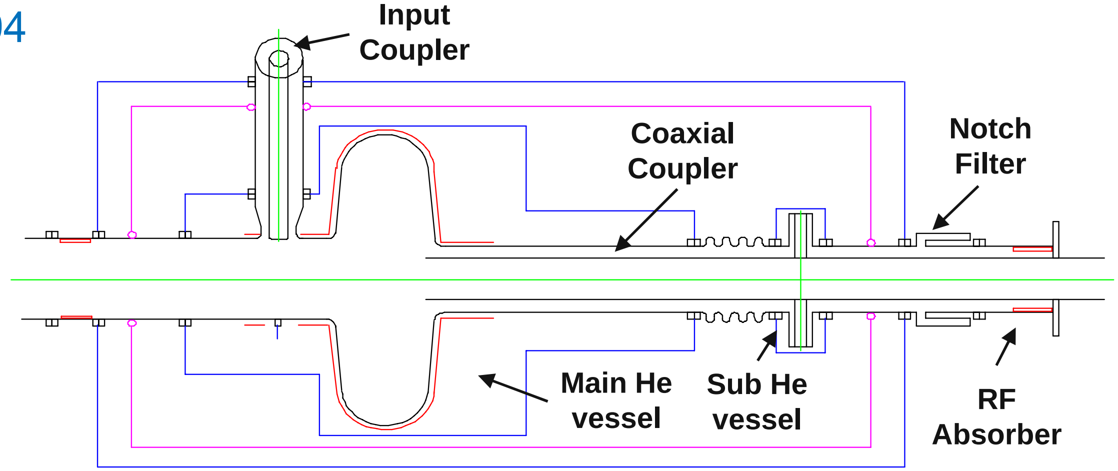


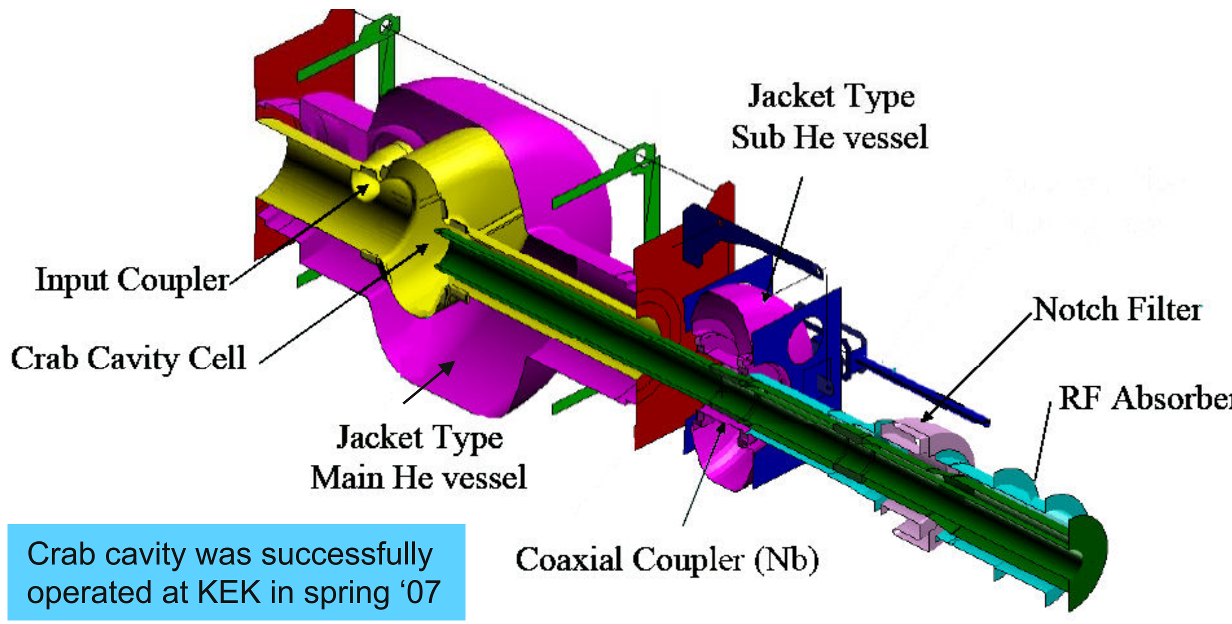
Slide courtesy: L. Morrison

KEK Single-Cell 500 MHz Crab Cavity*

1/3-scale prototyping started in 1994

Frequency (MHz)	501.7
Deflecting Voltage	1.44 / 1.41 MV
G	220
R / Q (Ω)	46.7
Min beam radius	10.0 cm
E_{sp}/V_{defl} (1/m)	14.4
B_{sp}/V_{defl} (mT/MV)	41.5





Crab cavity was successfully operated at KEK in spring '07

* K. Hosoyama, KEK

SRF Deflecting Cavities

Proceedings of EPAC 2002, Paris, France

RF DELECTING CAVITY DESIGN FOR BERKELEY ULTRAFAST X RAY SOURCE *

Derun Li and J. Corlett, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

$(R/Q)_{\perp}$	350	Ω
Q_0	2×10^9	
Active length/cavity	26.92	cm
Deflecting gradient	5	MV/m
Transverse voltage/cavity	1.346	MV
Power dissipation at 2 K	2.6	Watts

Cavity frequency	3.9	GHz
Phase Advance per cell	180°	Degree
Cavity Equator Curvature	1.027	cm
Cavity Radius	4.795	cm
Cell length	3.846	cm
Iris Radius	1.500	cm
Beam pipe radius	1.500	cm
TM mode cut-off frequency	7.634	GHz
TE mode cut-off frequency	5.865	GHz

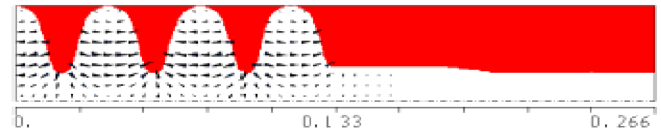


Figure 1. Electric field distribution of the deflecting mode for a 7-cell cavity

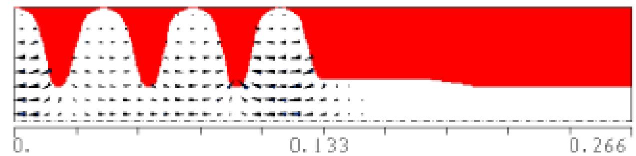


Figure 2. E-field of monopole LOM at 2.8581 GHz

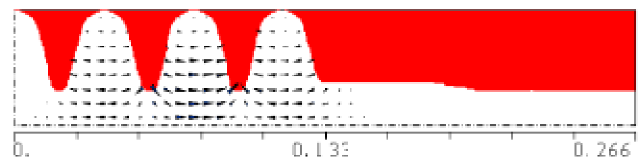
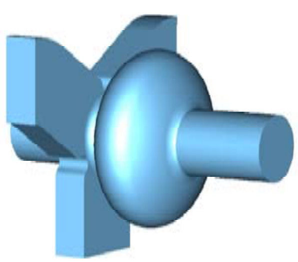
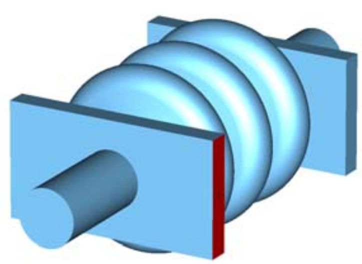
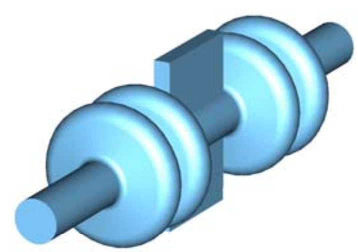
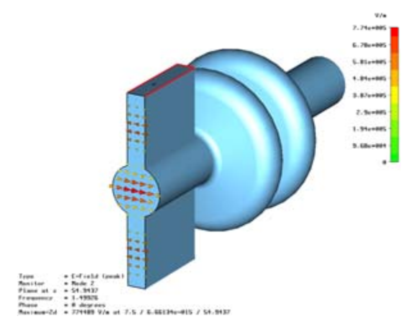


Figure 3. E-field of monopole LOM at 2.8685 GHz



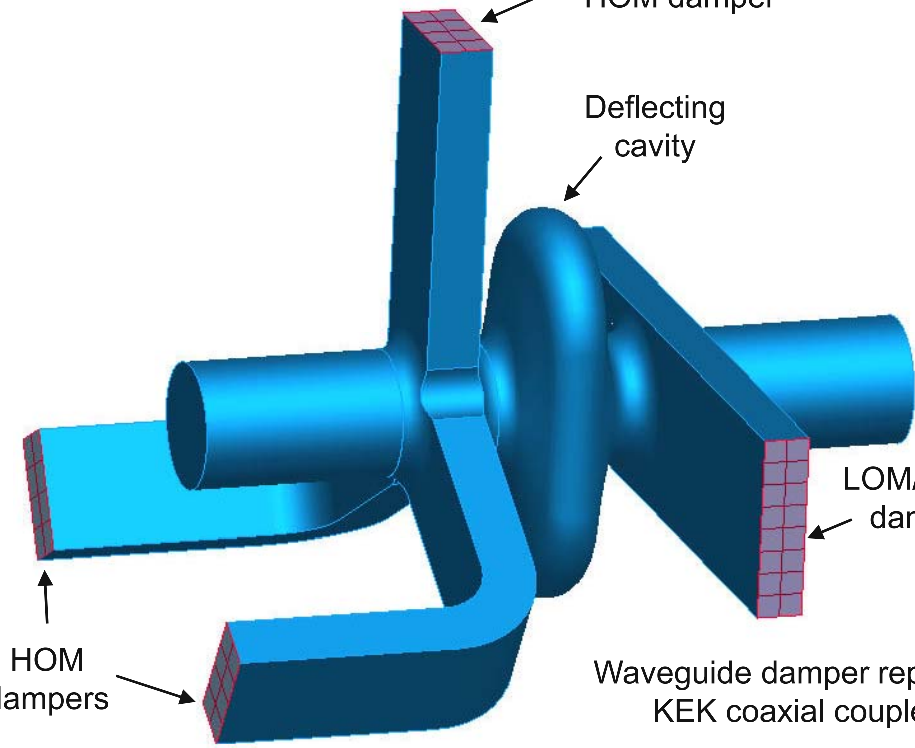






APS 2.8 GHz Superconducting Single-Cell Deflecting Cavity[1]

Frequency (GHz)	2.815
Deflecting Voltage	4 MV * 2
Qo (2K)	$3.8 * 10^9$
G	235
R_T / Q (Ω/m)	37.2
Beam radius	2.5 cm
No. Cavities	12 * 2
Operation	CW
Beam Current (mA)	100
E_{sp}/V_{defl} (1/m)	83.5
B_{sp}/V_{defl} (mT/MV)	244.1

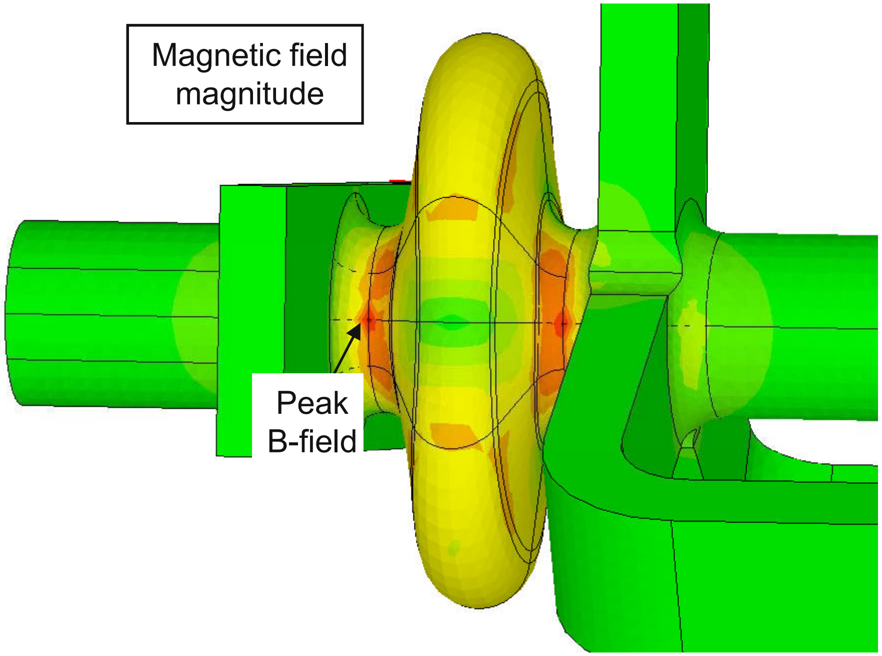


Compact single-cell cavity / damper assembly

[1] In collaboration with JLab and LBL

Deflecting Mode

- Dampers create a 37% increase in peak magnetic field
- Strong damping requirements for APS necessitate damper proximity to cavity
- Total number of cavities is determined such that peak magnetic field is < 100 mT
- 12 mm clearance between cavity and dampers (on either side) for tuning plates.
- An elliptical beam pipe was investigated for reducing peak magnetic field, but little improvement was found in the ratio mT/MV.

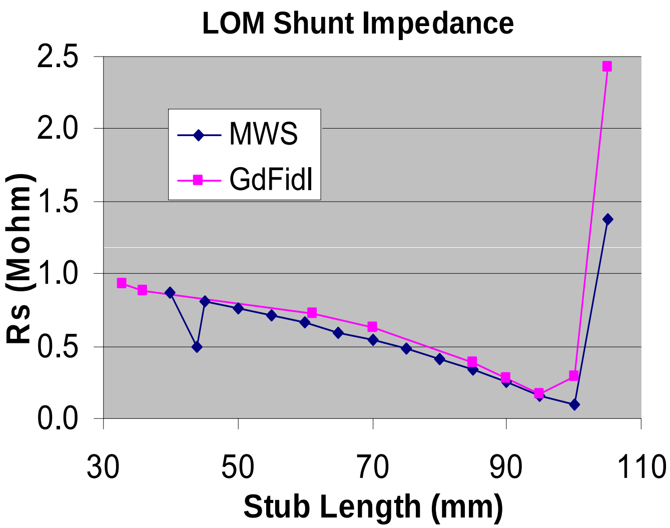


	Peak mt/MV	Rt/Q	G
1-cell	178.8	36.3	239
1-cell w/ LOM	244.1	37.2	235

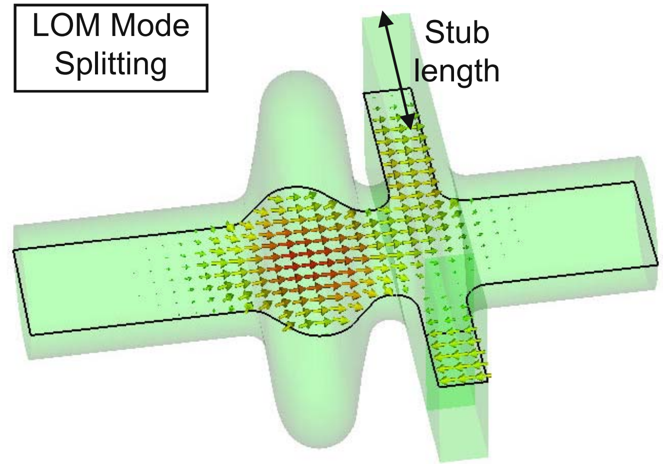
Deflecting mode parameters with and without dampers

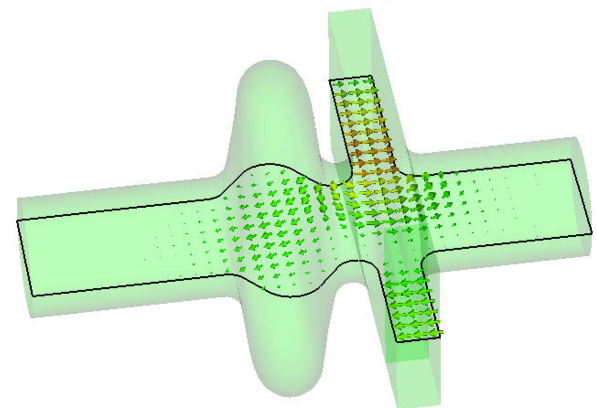
Lower Order Mode

- Deflecting mode couples weakly to LOM waveguide
- LOM waveguide stub was optimized exclusively for LOM damping
- LOM splits into two modes as the stub length approached optimal value
- Nominal stub length was 95 mm, or ~ $\frac{3\lambda}{4}$



Microwave Studio and GdFidl results from varying stub length



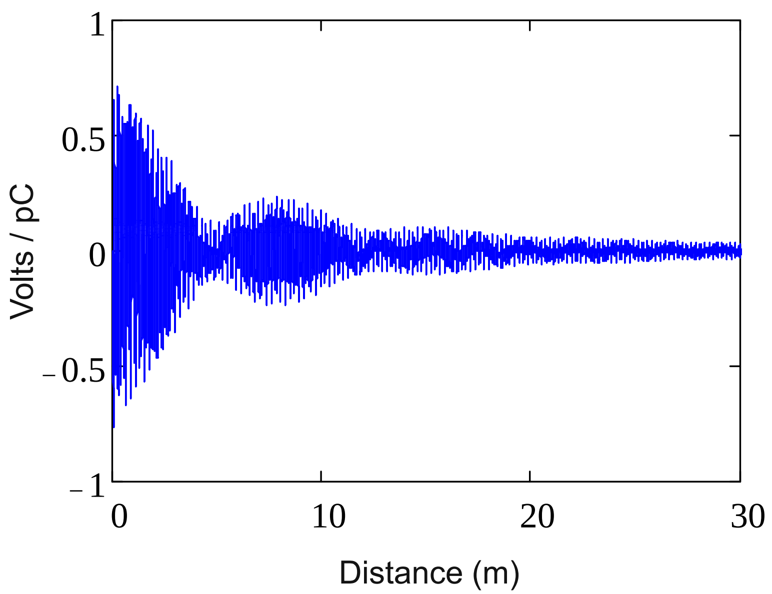


	Freq (GHz)	Qext	R/Q
1-cell	2.4	----	68.9
1-cell w/ LOM	2.4	231	55.1
	2.46	99.1	24.2

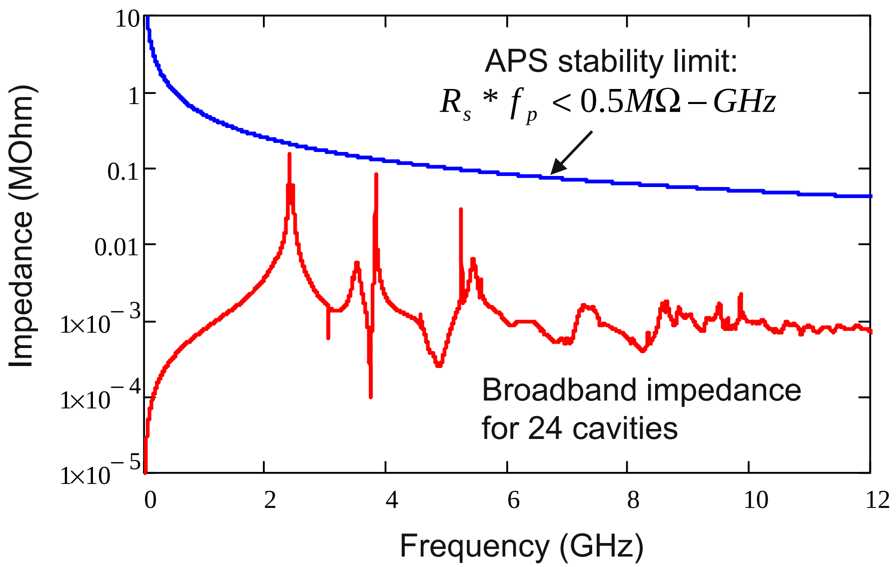
Lower-order-mode parameters with and without dampers

Deflecting Cavity Broadband Longitudinal Impedance

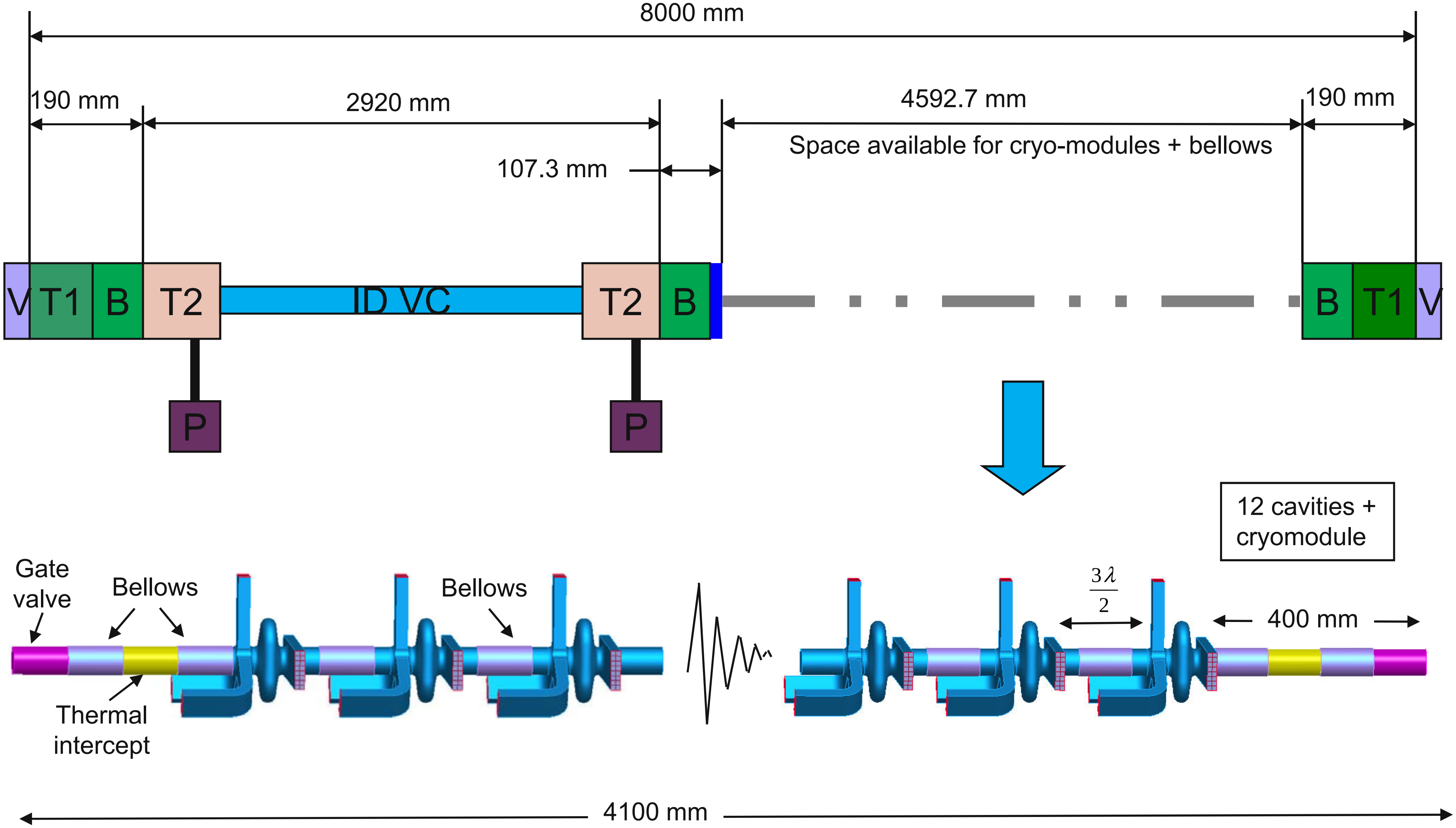
Longitudinal Wakefield Dissipation



APS Longitudinal Beam Stability



Deflecting Cavity Layout - Schematic



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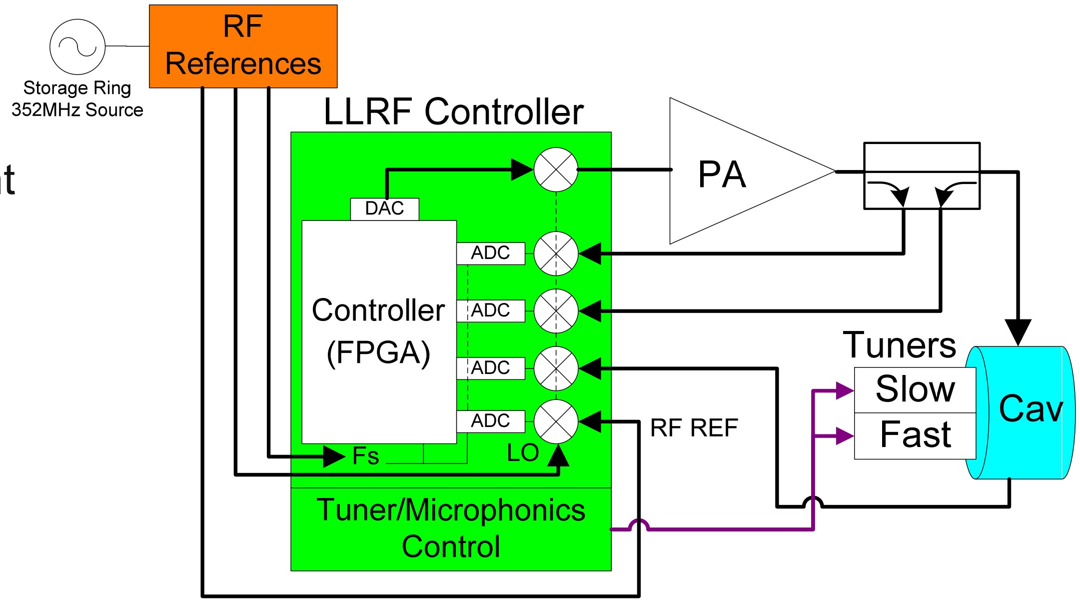
CW SRF - RF Control Challenges

- Differential Phase Error Specification: ±0.04 deg
- Differential Voltage Error Spec: ±0.29 %
- Architecture Tradeoffs:
  - Single Drive Amplifier: Correlated errors cancel, but need individual I/Q modulators
  - Individual Drive Amplifiers: Provides individual low level control, but residual phase noise is uncorrelated.
- Self-Excited Loop & Tuner Control Algorithms for fast recovery from quench/trips in presence of large static Lorentz detuning (JLab has made excellent progress in this area)
- Microphonics Mitigation
- Calibration Algorithms (cancel kick, reduce drift)
- Phase stable reference & cable plant
- Low noise down-conversion



Slide courtesy T. Berenc

Summary

- The short X-ray pulse generation at the synchrotron light sources will open up new frontiers in time domain science using X-ray techniques to study structural dynamics included but not limited to:
  - Condensed Matter, Chemical and Biological, Gas Phase Dynamics
- Zholents' scheme has been considered by the synchrotron facilities (ALS, Spring8, ESRF, DIAMOND, ANL) and as applied to the Advance Photon Source has been studied extensively
- Both normal conducting room-temperature and SRF option are feasible with significant advantages of SRF
  - Is not limited to SR bunch trains fill patterns
  - Higher flux and higher repetition rates up to CW
- It is complimentary to LCLS with the added advantage of energy tunability which is a unique feature in comparison to XFEL sources
  - Provides spectral coverage and resolution that is necessary in detecting electronic and nuclear geometry on ps-time scale
- Light source-based short x-ray pulse generation via Zholents' scheme has the capability of accommodating multiple users
- ANL-APS is taking a lead to develop an SRF deflecting system generating ps-type x-ray pulses in collaboration with JLab and LBL
- We welcome and invite more collaborators to join this effort.